A National Oceanographic Partnership Program Award

HYCOM Consortium for Data-assimilative Ocean Modeling

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Long-Term Goals

Make HYCOM (HYbrid Coordinate Ocean Model) a state of the art community ocean model with data assimilation capability that can (1) be used in a wide range of ocean-related research, (2) be used in a next generation eddy-resolving global ocean prediction system and (3) be coupled to a variety of other models, including littoral, atmospheric, ice and bio-chemical.

Objectives

Collaborative 5-year (FY00-04) National Ocean Partnership Program (NOPP) project on the development and evaluation of HYCOM, a scalable and data-assimilative generalized (hybrid isopycnal/terrain-following (σ)/z) coordinate ocean model. Work with collaborators Eric Chassignet (overall project lead PI) and his group at the University of Miami, Rainer Bleck (Los Alamos National Laboratory), Ole Martin Smedstad (Planning Systems, Inc.), Carlisle Thacker (NOAA/Atlantic Oceanographic and Meteorological Laboratory) and Remy Baraille (SHOM). Apply HYCOM to two model domains, an eddy-resolving Atlantic domain (with ~7 km resolution at mid latitudes) and a coarser resolution global domain.

Approach

This includes many aspects of the ocean modeling that will be performed by or in collaboration with consortium partners and partnering projects (five at NRL in FY02). The data assimilation components are covered in other HYCOM related ONR reports.

1. Ocean model design: HYCOM is a generalized (hybrid isopycnal/σ/z) coordinate ocean model. It is isopycnal in the open stratified ocean, but reverts to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates near the surface in the mixed layer. This generalized vertical coordinate approach is dynamic in space and time via the layered continuity equation, which allows a dynamical transition between the coordinate types. Like MICOM, HYCOM allows isopycnals intersecting sloping topography by allowing zero thickness layers. HYCOM was developed from MICOM using the theoretical foundation for implementing a hybrid coordinate system set forth in Bleck and Boudra (1981), Bleck and Benjamin (1993), Bleck (2002) and Halliwell (2002).

2. Model development: HYCOM development is a close collaboration between Los Alamos (Rainer Bleck), NRL (Alan Wallcraft) and the University of Miami (George Halliwell), where the person in parenthesis is the lead performer in each group. Alan Wallcraft is in charge of developing and maintaining the standard version of the model, one that is scalable/portable and

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can run on the latest computer architectures. Part of this work will be performed under a partnering Common HPC Software Support Initiative (CHSSI) project. HYCOM will be maintained as a single source code with the maximum feasible backward compatibility. Salient issues include the mixed layer and diapycnal mixing, the hybrid coordinate generator, developing a portable and scalable computer code, the capability to run HYCOM in MICOM-mode, the ability to initialize HYCOM from MICOM-mode or a true MICOM simulation, and diagnostic/visualization capabilities. A grid nesting capability is under development in a collaboration between U. Miami and a partnering project at NRL, the 6.2 Global HYCOM and Advanced Data Assimilation project sponsored by ONR (see separate report).

3. Ocean modeling applications: HYCOM will be applied to the Atlantic Ocean (28°S-70°N) in a close collaboration with Eric Chassignet's group and the global domain in collaboration with Rainer Bleck and Eric Chassignet. HYCOM has been tested on a 1/3° Atlantic model grid consistent with the DYNAMO Experiment before going to high resolution. The HYCOM results will be compared to simulations run using MICOM (Chassignet and Garraffo, 2001). The high resolution grid is .08° cos θ in latitude (θ) by .08° in longitude or ~7 km resolution for each variable at mid-latitudes. The high resolution Atlantic modeling will be performed mainly using a large grant of computer time provided by an FY02-04 DoD High Performance Computing (HPC) Challenge project with Eric Chassignet as the lead PI. NRL participation in the global modeling will begin in FY02 with .72° equatorial resolution. Later it will be increased to .24° and in FY04 to .08° in collaboration with partnering projects. Atmospheric forcing (wind and thermal) will be used from both the European Centre for Medium Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP). A wide range of data sets are available for model evaluation (Chassignet et al., 2000; Hurlburt and Hogan, 2000) and these papers discuss a wide range of climatological model-data comparisons. In addition, we have long time series of transports through the Florida Straits, sea level at tide gauges, and SST and subsurface temperature from moored buoys; also altimetric sea surface height (SSH) and IR SSTs from satellites, PALACE float and BT data and data from research field programs.

Work Completed

Two meetings of the HYCOM/NOPP partnership were held (Nov. 2001 and Feb 2002) to review progress and update the plans and milestones, technical issues, and responsibilities of the participants.

Model development and basic testing: Alan Wallcraft completed development of HYCOM 2.1 and it was released in Sept. 2002. This development included contributions from other NOPP/HYCOM consortium partners (see separate ONR reports), a 6.2 ONR Naval Ocean Modeling and Prediction (NOMP) project (HYCOM and advanced data data assimilation; see separate ONR report), and a 6.3 CHSSI project. A major aspect was development aimed at making the standard version of HYCOM ready for application as a fully global ocean model. Halos were added for MPI to automatically support periodic boundaries (6.3 CHSSI project). The capability to handle orthogonal curvilinear grids was added and used to create a bi-polar (PanAm) grid to cover the northern polar region. It matches the spherical grid convering the remainder of the global ocean at 47°N. Other salient additions to HYCOM 2.1 include support for nested-domain open boundaries (6.2 NOMP project), Mellor-Yamada 2.5 (Mellor and Yamada, 1982) and Price-Weller-Pinkel (Price et al., 1986) as new embedded mixed layer options (NOPP/HYCOM/U. Miami), support for multiple tracers, and NetCDF output files (6.3 CHSSI project).

For testing HYCOM 2.1 has been set up on a global domain with .72° equatorial resolution and 26 layers. It has been run for 5.5 years starting from the Levitus 1994 climatology (Levitus et al., 1994; Levitus and Boyer, 1994) with ECMWF high frequency climatological forcing. The high frequency climatological forcing was formed by adding the 6-hourly deviations from temporally interpolated monthly means for a specific year (Sept. 1994 – Sept. 1995) to a temporally interpolated monthly ECMWF climatology formed from the 1979-1993 ECWMF reanalysis. An energy loan sea ice model is used, a component scheduled for upgrade to the state-of-the-art Los Alamos/NCAR ice model during FY03.

Atlantic modeling (28°S-70°N): A 1/12° (~7 km mid-latitude resolution) eddy-resolving Atlantic Ocean model with data assimilation is a major goal of this NOPP project. During FY01 the Atlantic modeling was at 1/3° resolution with a ~2 mo run at 1/12° resolution. During FY02 an FY02-04 DoD HPC Challenge project was used to run 1/12° Atlantic HYCOM 8.4 years in a sequence of 3 experiments, 2+ years with monthly climatological ECWMF forcing, 3 years with 6-hourly high frequency monthly climatological forcing and July 1999 - July 2002 with 3 or 6 hourly hybrid Fleet Numerical Meteorology and Oceanography Center (FNMOC)/ECMWF forcing, where the FNMOC mean wind stress over 1990-2001 is replaced by the ECMWF reanalysis mean. The first of these HYCOM simulations was initialized from the best 1/12° MICOM Atlantic simulation and the other two from the preceding experiment. The first experiment was set up to emulate the MICOM experiment as closely as possible. Contributions to the meridional overturning from outside the model domain were included via relaxation to Levitus temperature, salinity and interface depth in 3° buffer zones along the northern and southern boundaries. The surface salinity forcing is a combination of evaporation-precipitation from COADS climatology and relaxation to the Levitus sea surface salinity climatology. Ice is included via a simple energy loan model. Since HYCOM can also be run in MICOM emulation mode, HYCOM was run for ~2 years in 1/12° Atlantic MICOM mode starting from the same MICOM state as the first of the 1/12° HYCOM Atlantic simulations. Ole Martin Smedstad used the July 1999-July 2002 Atlantic HYCOM simulation to initialize a data-assimilative 1/12° Atlantic HYCOM run (see separate NOPP/HYCOM/PSI ONR report).

Results

The collaborative HYCOM effort including the HYCOM/NOPP consortium, partnering projects and the broader international community effort is working extremely well. It should be noted that advanced data-assimilative ocean modeling and prediction has become sufficiently complex that a multi-agency, multi-institutional consortium of expertise is essential. The National Ocean Partnership Program is proving an outstanding means to support such collaborations.

HYCOM 2.1 is scalable up to O(1000 cpus) via two levels of parallelization, either or both of which can be used, and it can run on computing platforms ranging from PCs to a variety of supercomputers with different parallel architectures. This was accomplished using a single source code for all machine types. HYCOM 2.1 supports a generalized (hybrid isopycnal/σ/z) vertical coordinate, orthogonal curvilinear "horizontal" coordinates, fully global ocean modeling using a bi-polar (PanAm) grid for the northern polar region, 4 mixed layer options, nested open boundaries, and multiple passive tracers.

The first 1/12° Atlantic HYCOM simulation was designed to emulate the best 1/12° Atlantic MICOM simulation which has a very realistic Gulf Stream pathway and slightly high for the meridional overturning (21 Sv) (Chassignet and Garraffo, 2001). Aside from the hybrid vertical coordinate, the major deviations from MICOM are the mixed layer and the sub-mixed layer diapycnal mixing scheme. HYCOM uses KPP (Large et al., 1997) for both while MICOM has a Kraus-Turner (Kraus and Turner, 1967) type mixed layer and an explicit diapycnal mixing scheme (McDougall and Dewar, 1998). The high frequency wind forcing in the second HYCOM experiment is another significant deviation, since it tends to enhance mixed layer deepening. The first experiment needs to overlap the second one to better assess the impact of that, but the needed extension of first experiment is not yet completed. While analysis of the results is still preliminary, the first 1/12° HYCOM experiments are able to simulate the main features of the Atlantic Ocean circulation from the mesoscale to large scale circulation and water masses, some quite accurately, others with significant quantitative but not qualitative errors. Although other factors may be important as well, early analysis indicates the main quantitative errors are linked to increased vertical mixing in the southern buffer zone (25°S-28°S). This increases the strength of the Atlantic meridional overturning cell (MOC) (which was slightly high in MICOM) to unrealistically strong (~27 Sv) in HYCOM with high frequency forcing. Figure 1 indicates that the northern buffer zone does not contribute to excessive meridional overturning and that HYCOM simulates the overflow from the Denmark Strait very realistically, including the southward transport through the Denmark Strait and the transport increases downstream due to entrainment and contributions from other straits. Cross-sections (not shown) depict cold, fresh water from the Nordic Seas flowing southward through the Denmark Strait, sinking along isopycnals and entraining warmer, saltier Atlantic water.

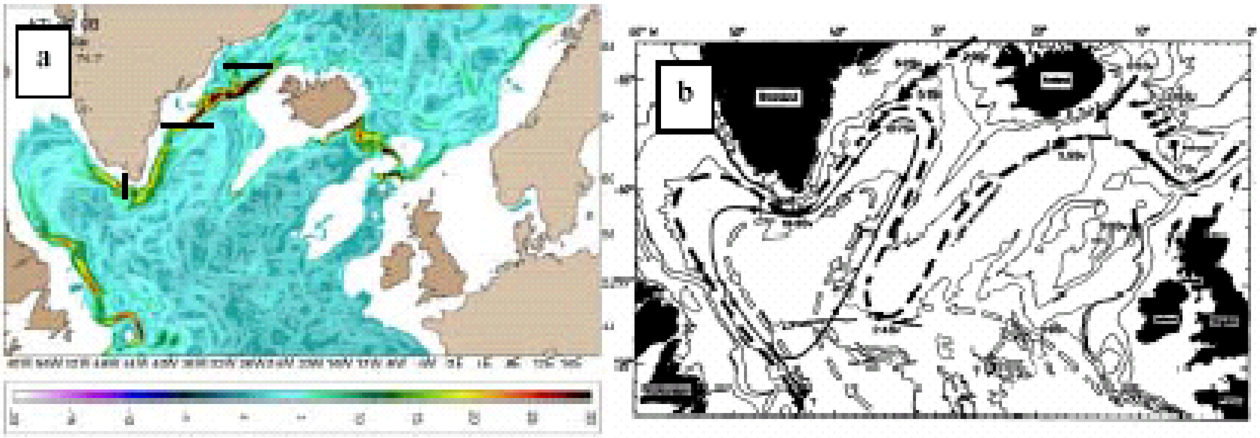

Figure 1. Southward deep transports in the Denmark Straits overflow region (a) simulated by 1/12° HYCOM vs. (b) observed using current meters (Dickson and Brown, 1994). Modelled (observed) transports (in Sv) across the sections marked by black bars on (a) are 4.1 (5.2) through the Denmark Strait, 9.4 (10.7) east of southern Greenland and 13.8 (13.3) at the southern tip of Greenland.

Accurate simulation of the Gulf Stream pathway between Cape Hatteras and the Grand Banks has been very challenging for ocean models. In the HYCOM simulations, the pathway parallels the observed and very accurate MICOM pathways and it lies within the one standard deviation pathway lines, but in a 2-year mean from the high frequency climatological simulation it is ~200 km too far south east of Cape Hatteras at 71°W. Using the dynamical mechanism of Thompson and Schmitz (1989), this is consistent with an excessively strong Deep Western Boundary Current associated with the strong MOC. Even though the MOC is too strong, the northward transport through the Florida Strait at 27°N is ~8% too weak (27 Sv vs. 32 Sv observed). This is consistent with a vertical MOC structure that is too deep and a transport that is lower than observed above the ~740 m sill depth (Malloy and Hurley, 1970) of the Florida Strait, so that part of the flow is diverted east of the Bahamas (~19 Sv vs. 5 Sv observed by Lee et al. (1996)). Still the mean velocities and vertical and horizontal structure of the flow entering the Gulf of Mexico through the Yucatan Channel (not shown) demonstrates excellent agreement with a cross-section based on 1 year of extensive measurements by (Sheinbaum et al., 2002). The extension of the 1/12° HYCOM experiment with monthly climatological forcing will be completed and the results of these experiments will be analyzed more thoroughly during FY03. Although the southern buffer zone relaxation may need some tuning, the next planned modeling step is to change the reference depth for potential density from the surface to 2 km depth and to add thermobaricity, both capabilities which already exist in HYCOM and MICOM. This is known to improve the vertical structure of the MOC and to reduce the strength of the upper meridional overturning cell (Chassignet et al., 2002).

Impact and Applications

The intended overall impact of the HYCOM/NOPP project was the development of a next generation hybrid (generalized) coordinate ocean model which would have a greater range of applicability than traditional single coordinate ocean models. The coordinate system design and its applications are outlined under APPROACH. The development was to include ocean data assimilation with a demonstration in the Atlantic at 1/12° equatorial (~7 km mid-latitude) resolution with and without data assimilation and a coarser resolution (non-eddy-resolving) global demonstration. As of this writing the project is well on its way to these goals, including the first near real-time 1/12° HYCOM Atlantic nowcast/forecast system with a web page that will soon be available to the public. Ultimately (via follow-on projects) the intended impact of this project is a next generation eddy-resolving global ocean prediction system with unprecedented capability. By the end of FY06 this system should be running at NAVOCEANO with 1/12° (~ 7 km mid-latitude) resolution and the resolution should increase to 1/25° (3-4 km at mid-latitudes) by the end of the decade. These systems would include an embedded ice model and the capability to host nested littoral models with even higher resolution. The HYCOM Consortium formed under the NOPP project and the wide range of Consortium expertise has been essential to the success of this effort.

To illustrate the overall impact of real-time global ocean products, the NRL Oceanography Division web page experienced over 10 million hits during 2002 , most of these to existing real-time global ocean nowcast/forecast products that were developed at NRL. These are now operational or pre-operational at NAVOCEANO (all developed outside NOPP). The products assimilate satellite altimeter sea surface height (SSH) data, satellite IR sea surface temperature (SST) and in-situ data. They include an operational first generation nearly global ocean prediction model which has ~7 km mid-latitude resolution, sufficient for nowcasts and 30-day forecasts of the ocean weather such as ocean eddies and the meandering of ocean fronts and currents. Ocean eddies are 20-30 times smaller than corresponding atmospheric low and high pressure systems. However, for computational feasibility this model has only 7 Lagrangian layers in the vertical and excludes the Arctic and most shallow water regions. This model helps constrain nowcasts of a pre-operational fully global ocean prediction model with coarser 15-16 km mid-latitude resolution but with 40 levels in the vertical. The web pages also show results of operational real-time satellite altimetry and model-independent analyses of SSH and SST.

HYCOM is designed to provide a major advance over the existing global ocean products, since it overcomes design limitations of the present systems as well as limitations in vertical or horizontal resolution. The result should be a more streamlined system with improved performance and an extended range of applicability (e.g. the present systems are seriously limited in shallow water and in handling the transition from deep to shallow water).

Many of the applications of ocean products listed below were intended apriori, but others were unanticipated and reported by users of the existing products. Some span multiple categories below and are listed first. Ocean nowcast/forecast systems play a vital role in the assimilation and synthesis of global satellite and in situ data and in using the results to make ocean forecasts. By participating in the multi-national Global Ocean Data Assimilation Experiment (GODAE) (2000-2007) the HYCOM Consortium is contributing to the GODAE goal of helping to justify a permanent global ocean observing system by demonstrating real-time global ocean products with a customer base. Other cross - cutting applications include optimal ship track routing; search, rescue and salvage; high resolution boundary conditions worldwide for even higher resolution littoral models; inputs or coupling to atmospheric, ice and bio-chemical models; inputs to shipboard environmental products; observing system simulation and assessment; iceberg tracking; El Niño monitoring and the prediction of El Niño generated equatorial and coastal trapped waves which have large weather and ecosystem impacts in locations as distant as the Alaskan coast.

National Security

Additional national security applications include anti-submarine warfare and surveillance, mine warfare, tactical planning, inputs to tactical decision aids, amphibious and autonomous underwater vehicle (auv) operations, marine safety and underwater forensics, some of these via boundary conditions and initial conditions to littoral models. Boundary conditions are also needed for nearshore and bay/estuary models for use in predicting dispersion of biochemical agents through waterways and for predicting water levels and currents.

Economic Development

Additional applications in the area of economic development include fisheries monitoring and fishing forecasts, and monitoring and prediction of eddies and currents that may impact deep ocean structures such as oil rigs as well as other offshore oil company operations.

Quality of Life

Additional applications under quality of life include pollution and tracer tracking such as oil spills, inputs to water quality assessment, ecosystem and marine resource management, location of blue whales in relation to ocean front and eddy features, currents for routing and safety of recreational watercraft such as sailboats and yachts, high current shear prediction for use in prediction of giant “rogue” waves and in at-sea refueling, and for scheduling of geophysical hazard surveys.

Science Education and Communication

Real-time and archived results from existing Navy global ocean products can be seen on the web page http://www.ocean.nrlssc.navy.mil/global_nlom. These and other NRL Oceanography division web pages received over 10 million hits during 2002. In addition, digital output is available. The same will soon be available from a prototype 1/12° Atlantic HYCOM prediction system. The HYCOM web page, http://hycom.rsmas.edu, already provides information about HYCOM, publications and presentations, HYCOM simulation results and the HYCOM source code. In addition, the NOPP project and partnering projects support postdocs and students, including a postdoc and a Ph.D student at NRL. Results from an existing Navy ocean prediction system have been used in an educational television program about El Niño and in a National Geographic article. Real-time and archived results from eddy-resolving global ocean prediction systems are contributing to increased understanding of the ocean circulation and have numerous applications in ocean research since they can track ocean features, including individual eddies, from generation to decay. Thus they can be used in guiding research measurement programs and in the interpretation of field program measurements, which are limited in space and time.

<u>Transitions</u>

National Security

The NRL group which is part of the HYCOM Consortium transitioned a nearly global ocean prediction system with ~7 km mid-latitude resolution and 7 Lagrangian layers in the vertical outside NOPP. NAVOCEANO has been running it in real time since 18 Oct. 2000 and it became an operational product on 27 Sept. 2001. A fully global HYCOM system with similar horizontal resolution and higher vertical resolution is already in Navy plans for transition to NAVOCEANO near the end of FY06.

Economic Development

Results from the existing operational system are available digitally and via the web page. They are being used in commercial fishing forecast products and efforts are in progress to make them part of a product used to assess the threat to oil rig operations from ocean eddies and currents. HYCOM should greatly expand interest in commercial applications.

Quality of Life

Results from the existing operational system are made available digitally and via the web.

Science Education and Communication

Results from a prototype near real-time 1/12° Atlantic HYCOM prediction system will be made available via a web page and a Live Access Server (LAS) in the near future. The HYCOM web page, http://hycom.rsmas.edu, already provides the HYCOM source code and information about HYCOM and HYCOM results.

Related Projects

The HYCOM/NOPP consortium includes E.P. Chassignet (Coordinator), A. Mariano, G. Halliwell (U. Miami), T.M. Chin (JPL/U. Miami), R. Bleck (LANL), H. Hurlburt, A. Wallcraft, P. Hogan, R. Rhodes, and G. Jacobs (Naval Research Laboratory), O. M. Smedstad (Planning Systems, Inc.), W.C. Thacker (NOAA/AOML) and R. Baraille (SHOM). Partnering projects at NRL include an NRL 6.1 ONR JES DRI project, 6.1 LINKS, 6.1 Dynamics of Low Latitude Western Boundary Currents, 6.1 Thermodynamic and Topographic Forcing in Global Ocean Models, 6.2 Global HYCOM and Advanced Data Assimilation, 6.3 High Fidelity Simulation of Littoral Environments (CHSSI)) and 6.4 Altimeter Data Fusion Center (ADFC) Support. Additionally, the project receives grants of HPC time from the DoD High Performance Computing Modernization Office, including an HPC challenge grant entitled “Basin-scale ocean prediction with the Hybrid Coordinate Ocean Model”. The NRL PI is a member of the International and U.S. GODAE Steering Teams.

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